International Journal of Civil Engineering (IJCE)
ISSN 2278-9987
Vol. 2, Issue 4, Sep 2013, 75-82

International Academy of Science, Engineering and Technology
Connecting Researchers; Nurturing Innovations

VIBRATRION CONTROL-ACTUATOR AND SENSOR PLACEMENT USING MODAL APPROACH – SOME EXPERIMENTAL INVESTIGATIONS

G. K. ARUNVIVEK, R. SARAVANAKUMAR, M. SENTHILKUMAR & M. LOGESH KUMAR

Assistant Professor, Department of Civil Engineering, K. S. R. College of Engineering, Erode, Tamil Nadu, India

ABSTRACT

Application of control technologies to structure is expected to able to enhance a structural performance in response to natural hazards. Specifically, smart base isolation system which consist of a semi-active isolator at the base with controllable semi devices attract much attention for efficacy and economical reasons. Focusses on the development of control design strategies using physical knowledge of system dynamics that had not been investigated systematically and applied for civil structures previously. Structural characteristics that are helpful to disclose structural properties, yet are often ignore by civil engineers are integrated with those control techniques in both nodal and modal co-ordinates to construct indices for the determination of the control action to take full advantage of their capabilities. A 3D isolated building model is employed with Magneto Rheological dampers are used as smart control device. IEPE piezoresistive Actuator and Force transducers are used with Deltatron conditioning amplifier.

A large number of techniques for the optimal placement of sensors and actuators in a vibration control system have been developed in recent years. Many of these methods are based on the concept of controllability observability. Changing the configuration of actuators and sensors can shape controllability and observability properties. This is an optimization problem that is closely related to achieving high performance with minimal cost. The establishment of explicit relationships between controllability and observability and vibration modes facilitates this approach. The experimental investigation employ the use of IEPE uniaxial accelerometers and triaxial accelerometer (Bruel & Kjare make) along with force transducers; mounted at different trial locations on the model structure to measure the absolute accelerations and damping force of the structure and rheological dampers respectively, mounted in the system, upon the excitation of structure.

This research paper explains the details of experimental work done out of the sponsored research project, proposes a controllability – observability – based approach for effective place control devices and sensors.

KEYWORDS: Actuators and Sensors, Earth Quake Hazards Mitigation, Modal Approach, Semi – Active Isolation, Vibration Control

INTRODUCTION

A large number of techniques for the optimal placement of sensors and actuators in a vibration control system have been developed in recent years. Many of these methods are based on the concepts of controllability and observability. Changing the configuration of the actuators and sensors can shape controllability and observability properties. This is an optimization problem that is closely related to achieving high performance with minimal cost. For example, a system in which actuators and sensors are placed at or near the nodes of vibration modes may require an exceptionally large control force, or even may be uncontrollable. This approach is facilitated by the establishment of explicit relationships between controllability and observability and vibration modes (Longman et al, 1982; Moor, 1981; Hamdan and Nayfeh, 1989, etc), among which Hamdan and Nayfeh's measures are particularly attractive. They introduced a generalized angle between the two vector spaces on which controllability and observability are based the left eigenvectors and the column vectors of input influence matrix, and the right eigenvectors and the column vectors of output measurement matrix. Choi et al (2000) further improved the method by extending the results to be used with a balanced coordinate system, and introducing the magnitude of the measures, the norms of eigenvectors, when used in that coordinate system. A balanced coordinate system is desirable because it ensures that the system is equally controllable and observable.

This paper will describe controllability-observability based approach proposed by Panossian et al. (1998) in a practical application and described in detail by Gawronski (1998). This approach involves the computation of the system norms of each device location for selected modes, and then grades them according to their participation in the system norm. It agrees with the control objective of the LQR algorithm to be used in this study, whose cost function is actually a 2-norm, and it is relatively simple compared with other algorithms.

The method proposed in this paper uses the Hankel singular norm instead of the $\boldsymbol{H_2}$ norms. The Hankel norm is advantageous because it reflects both controllability and observability, and is invariant under linear similarity transformations. The placement indices proposed by Gawronski (1998) took into consideration the closed-loop effects when the actuators are not placed at the disturbance location and sensors are not at the performance evaluation locations in index normalization. To make the approach more applicable to civil engineering problems, this study considers only the case when the actuators are collocated with disturbances and sensors collocated with performances. This assumption simplifies the normalization procedure.

Effects of the Cross Couplings on Norms in the Feedback Loop

A structure's inputs are composed of both disturbance and control inputs, and plant outputs include regulated outputs and measurements. In engineering practice, control devices and sensors are placed at available location, not necessarily collocated with the disturbance and outputs used for performance evaluations. It is shown that the cross couplings between the inputs and outputs all impact on the structural norms due to the feedback loop (Gawronski, 1998), so it is necessary to examine these effects for placement rules based on properties of the structural norms.

First, define a general model of a feedback control system that explicitly includes the desired inputs and outputs.

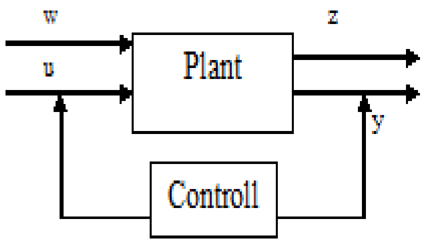

Figure 1: General Diagram of a Feedback Control System

The controller generates the control input u to the plant. The output consists of the regulated output **z** and the measurement output **y**. The feedback loop is closed between the measurement output and controller (actuator). In general, the measurement output is distinct from the regulated output, though they may be identical in some applications. The state model of the plant for the closed-loop system in Figure 1 is

$$\dot{x}(t) = Ax(t) + [B\ E]\begin{bmatrix} u(t) \\ w(t) \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} z(t) \\ y(t) \end{bmatrix} = \begin{bmatrix} C_z \\ C_y \end{bmatrix} x(t) + \begin{bmatrix} D_z & E_Z \\ D_y & E_y \end{bmatrix} \begin{bmatrix} u(t) \\ w(t) \end{bmatrix} \tag{2}$$

Let $\mathbf{G}_{wz}$ be the transfer function matrix from **w** to **z,** $\mathbf{G}_{wy}$ be the transfer function **w** to y, $\mathbf{G}_{uz}$ be the transfer function matrix from **u** to **z, and** $G_{\mathbf{uy}}$ be transfer function matrix from **u** to **y.** These open-loop transfer functions are expressed by

$$G_{uz}(s) = \mathbf{C}_Z(sI - A)^{-1}B+D_Z \tag{3}$$

$$G_{uy}(s) = \mathbf{C_y}(sI - A)^{-1}B+D_y$$

$$G_{wz}(s) = \mathbf{C}_Z(sI - A)^{-1}E+E_z$$

$$G_{wy}(s) = \mathbf{C_y}(sI - A)^{-1}E+E_y$$

The closed-loop transfer function from **w** to **z** then becomes

$$G_{\mathbf{wz\text{-}cl}} = G_{\mathbf{uz}} (I-G_{\mathbf{cy}} G_{\mathbf{uy}})^{-1} K G_{\mathbf{wy}} + G_{\mathbf{wz}} . \tag{4}$$

Equation (4) shows that the controller impacts the closed-loop performance not only through the action from **u** to **y,** but also through the cross-actions from **u** to **z** and **w** to **y.** If the transfer function matrics $\mathbf{G}_{wy}$ or $\mathbf{G}_{uz}$ were zero, the controller could not reach the response. Therefore, for non-collocated systems, the actuator and sensor connectivity $\mathbf{G}_{uy}$ is not the only factor that determines the closed-loop performance. This makes the placement problem complicated because the above effort would be in vain if $\mathbf{G}_{wy}$ or $\mathbf{G}_{uz}$ decreases while the importance of location (placement indices) is determined by large $\mathbf{G}_{uy.}$

Denote subscript i for the ith mode, the following multiplicate property of modal norms holds (Gawronski, 1998)

$$\|\mathbf{G}_{wz,i}\|\|\mathbf{G}_{uy,I}\| \cong \|\mathbf{G}_{wy,I}\|\|\mathbf{G}_{uz,I}\| \tag{5}$$

Where ||.|| denotes either H_2, $H\infty$, or Hankel norms, and subscript I denotes the ith mode.

This property can be shown directly using the approximate relationship between the transfer functions. This property indicates that for each mode the product of norms of the performance loop (from disturbance to response) and the control loop (from actuators to sensor response) is approximately equal to the product of the norms of the cross-couplings between the disturbance and sensors, and between the actuators and performance. It also indicates that improvement in $\mathbf{G}_{uy}$ automatically leads to improvement in $\mathbf{G}_{\mathbf{wy}}$ and $\mathbf{G}_{uz.}$ Thus, manipulating $\mathbf{G}_{uy}$ alone can perform the actuator and sensor location problems. This conclusion is important for the placement problem. Equation. (4) denote the Laplace transforms of the transforms of the vectors y, z, u and w with capital letters. The transfer function of the plant is then

$$\begin{bmatrix} Z \\ Y \end{bmatrix} = G(s) \begin{bmatrix} U \\ W \end{bmatrix} = \begin{bmatrix} G_{uz} & G_{wz} \\ G_{uy} & G_{wy} \end{bmatrix} \begin{bmatrix} U \\ W \end{bmatrix} = \begin{bmatrix} G_{uz}\, U + G_{wz} & W \\ G_{uy} U + G_{wy} & W \end{bmatrix}. \tag{6a}$$

The transfer function of the controller is

$$U = \begin{bmatrix} G_{cr} & G_{cy} \end{bmatrix} \begin{bmatrix} R \\ Y \end{bmatrix} = G_{cr}\, R + G_{cy}\, Y. \tag{6b}$$

Substituting Y from the second equation of (4) into above equation yields

$U = (I - G_{cy} G_{uy})^{-1} G_{cy} G_{wy} W.$ (7)

Substituting equation (6) into the first equation, yields the closed –loop transfer function from w to z of the feedback control system.

$Z = (G_{uz} (I - G_{cy} G_{uy})^{-1} G_{cy} G_{wy} + G_{wz}) W.$ (8)

If $G_{cy} = K(s)$, the transfer function diagram is shown in figrue 2.

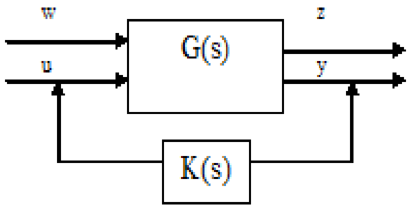

Figure 2: Diagram of a Constant – Gain Feedback Control System

PLACEMENT INDICES

To define the controllability-absorbability based actuator and sensor location model, information about the location and size of the actuator is in the control input influence matrix B. Information about the sensor location is contained in the matrix C is needed. The placement strategy here only considers the case that actuators are collocated with the disturbance, and sensors are collocated with the performance outputs.

For this benchmark problem, control devices are required to be placed at base level and conveniently, at bearing locations. So there are candidate locations for control devices. Accelerometers may be placed at the four corners of each floor including the base. Each corner has one accelerometer in the x- and one in the y- direction, giving twelve available accelerometer locations for each floor. Note that three sensors would be enough for each floor to capture the responses because each floor has three DOFs. Thus, the problem of placement is to determine a reasonable subset of locations for control devices that offer high controllability of the desired modes, and a reasonable subset of sensors that offer high absorbability in detection of the desired modes.

For each mode, the Hankel norm with a set of actuators or sensors is the *rms* sum of the Hankel norm with each single actuator or sensor from this set, i.e.,

$$r_i = \sqrt{\sum_{j=1}^{s} \gamma_{ij}^2} \text{ or } \gamma_i = \sqrt{\sum_{k=1}^{r} \gamma_{ik}^2} \quad (9)$$

Finally, the Hankel norm of the system is the largest norm of its mode, i.e.,

$$\|G\|_h \cong \max_i \|G\|_h = \gamma_{max} = 0.5 \|G\|_\infty. \quad (10)$$

Where γ_{max} is the largest Hankel singular value of the system. Equations 09 and 11 provide a means to normalize the indices using Hankel norms so that the indices are between) 0 and 1.

For actuator placement, the index σ_{ij} that evaluates the *j*th actuator at the *i*th mode in terms of Hankel norm is defined with respect to all modes and control devices as

$$\sigma_{ij} = \frac{\| G_{ij} \|_h}{\| G \|_h}. \quad (11)$$

Similarly, in the sensor placement, the placement index that evaluates the *k*th sensor at the *i*th mode is defined as

$$\sigma_{ij} = \frac{\| G_{ik} \|_h}{\| G \|_h} . \tag{12}$$

Locations in the neighborhood are not necessarily the best choice because the performance gains achieved using devices at these locations can also be achieved by appropriate gain adjustments (Gawronski, 1998). The best strategy is to find locations that cannot be compensated for by gain adjustment. Naturally, correlation coefficients are used to remove highly correlated locations.

Define a vector of the squares of the *i*th Hankel modal norms,

$$g_i = \begin{bmatrix} \| G_{ij} \|_h^2 \\ \| G_{i2} \|_h^2 \\ \vdots \\ \| G_{in} \|_h^2 \end{bmatrix} \tag{13}$$

where $\|G_{ik}\|_h$ is the Hankel norm of the k^{th} mode at the i^{th} control device or sensor. The correlation coefficient ρ_{ik} is defined as

$$\rho_{ik} = \frac{g_i^T g_k}{\| g_i \|_2 \| g_k \|_2}, \; i = 1,\ldots, r, \; k = i+1, \ldots, r. \tag{14}$$

Given a small positive number ε, say $\varepsilon = 0.001$, denote the membership index I(k), $k=1, \ldots, r$, where *r is the number of sensors (contol devices)*. This index is determined as

$$I(k) = \begin{cases} 0, & \rho_{ik} \\ 1, & \text{elsewhere} \end{cases} \quad \text{and } \rho_k < \rho_i \text{ for } k > i. \tag{15}$$

If I(k) =1, then the *k*th sensor (actuator) is accepted. If I (k) =0, the *k*th sensor (actuator) is rejected. In the case of I (k) = 0, the two locations *i* and *k* are either highly correlated ($\rho_{ik} > 1 - \varepsilon$), or the *i*th location has a higher performance σ_i.

Based on the above analysis the placement strategy is established. For this 3D base isolation benchmark problem, sensor placement is more flexible, so actuator locations are decided first. The procedure is described as follows:

- Place the control devices in order at the bearing locations, one in the *x*- direction and one in the *y*-direction. Assume each admissible sensor location has two sensors, one in the *x*- and one in the *y*-direction, so that the C_m matrix is fixed. For each location, compute the modal B_m matrix and then the Hankel placement indices for all modes, until the 42×12 (total 27 modes) placement index matrix is formed.
- Roughly choose 20-25 locations with the largest placement indices in the lower modes.
- Check the correlation coefficients for the selected locations. Reject actuators with I(k) = 0. The resulting values (say, 10) are the final locations. If the number is less than 10, add more locations in step2; if the number is more than 10, decrease the locations, so that rejection condition is stricter.
- Fix the B_m matrix for resulting set of actuator locations. Compute the floor sensor placement indices, assuming

sensors are put at all four corners on this floor while none are on other floors to determine C_m matrix. Repeat for each floor until the 9×27 placement index matrix is formed.

- Reject insignificant floors that have very low sensor placement indices.
- For the remaining floors, compute the corner plane indices one by one. Retain the non-correlated corners.

All control device and sensor locations are thus determined, following the above procedure.

Control Device and Sensor Placement for the Benchmark Problem

The 3D dynamics of the benchmark problem have, the parameters of the superstructure are known. The optimal isolation parameters, bearing stiffness and damping coefficient of the rheological dampers, have been determined. The experimental set up is as shown in photograph.

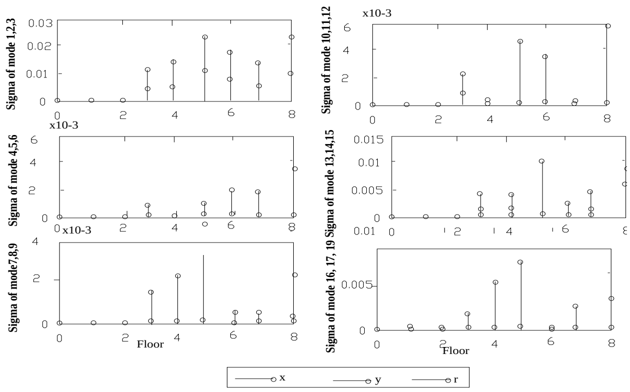

Figure 3: Sensor Placem Ent Indicves v.s. Floors

There are four corners, and thus eight available locations for accelerometers for each floor, some of which are redundant. Three accelerometers per floor (6 total accelerometers) would provide a measure of all motions of that particular floor. So the following step is to compute the corner indices of floors 3 to 8. Place two accelerometers (One in the x-direction and one in the y-direction) at each corner of floor 3 and compute the indices and then repeat this procedure for the remaining floors.

To evaluate the performance with the reduced set of sensors, comparisons are performed for responses of the isolated benchmark building. The control algorithm is chosen as LQG, and MR dampers are adopted as the control devices to examine the performance of these systems. Weights are placed on the corner base drifts, corner base accelerations, and corner top floor accelerations ($q_{drift} = 4.642 \times 10^8$, $q_{accelration} = 1.145 \times 10^9$, R= $I_{20\times20}$, $S_{\ddot{x}_g \ddot{x}_g} = 25I_2$, and $S_{v_i v_i} = I_{ns\times20}$, where *ns* is the number of sensors). Noise in the sensors is simulated by adding a band limited white noise to each signal that is scaled to have an RMS of approximately 3% of the corresponding maximum RMS responses of the passive system. Time history responses of the base drift, inter-story drift between the II and III floors, and roof accelerations at corner 1 in the *x*-direction for full sensor placement and reduced sensor placement are measured. If can be seen that the response values are very close and differences in the resulting performance of the two systems are not significant.

CONCLUSIONS

A controllability / observability –based approach has been proposed to effectively place control devices and sensors. The placement indices are based on Hankel singular values, which are invariant for both unbalanced and balanced systems. Validation of the technique for control device (MR dampers) not collocated with disturbances, correlations between locations are examined to avoid duplication of control effort, and locations with high indices and high correlations are rejected. The efficacy of the reduced set of sensors is confirmed by earthquake responses, Simulated with structural excitation using Dynamic signal analyzer.

REFERENCES

1. Akbay, Z .and Aktan. H. M.(1990). *"*Intelligent Energy Dissipation System". Proc. of the fourth U. S. National conference on Earthquake Engineering, Vol.3, No.4. pp 427-435.
2. Carlson, J.D. and Weiss, K. D.(1994). "A Growing Attraction of Magnetic Fluids", Machine Design, August, pp. 61-64.
3. Cherry, S.(1994). "Research on Friction Damping at University of British Columbia." Proceedings of International Workshop on Structural Control, USC Publication Number CE-9311, PP. 84-91.
4. Dyke, S. J., B. F. Spencer, Jr., M. K. Sain and Carlson, J.D.(1996a). "A New Semi-Active Control Device for Seismic Response Reduction," Proc.11th ASEC Engrg. Mech .Spec. Conf., Ft Lauderdale, Florida.
5. Dyke, S. J., B. F. Spencer, Jr., M. K. Sain and Carlson, J.D. (1996b) "Seismic Response Reduction using Magneto Rheological Dampers," Proc. of the IFAC World Congress, San Francisco , California.
6. Ehrgott, R.C. and Masri, S.F. (1994). "Structural control Applications of an Electro Rheological Device" Proceedings of International Workshop on Structural Control, USC Publication Number CE-9311, PP.115-129.
7. Fedorov, V. A.(1992). "Features of Experimental Research into Characteristics of Magneto Rheological and Electro Rheological Shock Absorbers on Special Test Stands." Manetohydrodynamics, Vol. 28, No.1, p.96.
8. Gamota D. R. and Filisko, F. E. (1991). "Dynamics Mechanical Studies of Electro Rheological Materials: Moderate Frequencies." Journal of Rheology, Vol. 35, PP.399-425.
9. Gavin, H.P.(1994). "Electro Rheological Dampers for Structural Vibration Suppression." Ph.D *dIssertation,* The University of Michigan, Department of civil and Environmental Engineering.
10. Kamnath, G. M., and Werely, N. M.(1996). "A Non Linear Viscoelastic-Plastic Model for Electro Rheological Fluids." Smart Materials and Structures, (Submitted).
11. Graselli, Y., Bossis, G. and Lemarie, E. (1993*).* "Field Induced structure in Magneto Rheological Suspensions." Progress in colloids & Polymer science.
12. Housner, G. W. and Masri, S. F.(Eds.).(1993) Proceedings of International Workshop on Structural Control, USC Publication Number CE-9311,Univ. of Southern California.
13. Housner, G. W. and Masri, S. F. and Chassiakos, A. G. .(Eds.).(1994). Proceedings of First World Conference on Structural Control, Pasadena, CA, August3-5.
14. Inaudi, J .A .and Kelly, J.M.(1994*)"* Experiments on Tuned Mass Dampers Using Viscoelastic, Frictional and Shape-Memory Alloy Materials." Proceedings of First World Conference on Structural Control, Pasadena, CA, August3-5.Vol.2, PP .TP3-107.
15. Kashevskill, B. E.(1990). "In Relaxtation of Viscous Stresses Magneto Rheological Suspensions." Manetohydrodynamics, Vol. 28, No.2, p.140.

16. Kawashima, K., Unjoh, S. and Shimizu, k.(1992). “Experimental on Dynamic Characteristics of Variable Damper.” proc. of Japan National Symposium on Structural Response Control, Tokyo, Japan.

17. Kordonsky, W. I. (1993b). “Magneto Rheological Effect as a Base of New Device and Technologies.” Journal of Magnetism and Magnetic Materials, Vol.122,No.1/3,p.395.

18. Kordonsky, W. I. Shulman, Z. P., Gorodkin, S. R. and Demchuk,.SA., Prokhoro I.V., Zaltsgendler, E.A. and Khusid, B.M.(1990). “Physical Properties of magnetizable structure Reversible Media.” Journal of Magnetism and Magnetic Materials, Vol.85,pp. 114-120.

19. Kurata, N., Kobori, T., Takahashi, M. Niwa, N. and Kurino, H.(1994) “Shaking Table Experiments of Active Variable Damping System.” Proceedings of First World Conference on Structural Control, Pasadena, CA, August3-5.Vol.2, PP .TP3-107.

20. Makris, N., Hill, D., Burton, S. and Jordon, M.(1995). “Electro Rheological Fluid Dampers for Seismic Protection of Structures.” Proc. SPIE Conf. on.” Smart struc T. and materials. (I. Chopra, Ed.), San Diego, California.184-194.

21. Makris, N., Hill, D., Burton, S. and Jordon, M. (1996). “Analysis and Design of an Electro Rheological Damper for Seismic Protection of Structures.” Journal of Engineering Mechanics, ASEC, (in press). MATLAB(1994). The Math Works, Inc. Natick, Massachusetts.

22. Minagawa, K., Watanabe, T. and Munakata, M.(1994). “A Novel Apparatus for Rheological Electro Measurements of Magneto Rheological Fluids.” Journal of Non Newtonian Fluid Mechanics, Vol.52, No.1, p.59.

23. Savost’yanov A. (1992). “Effects of Magnetomechanical Relaxation in a Magneto Rheological Suspension.” Magnetohydrodynamics. Vol.28, No.1, p.42.

APPENDICES

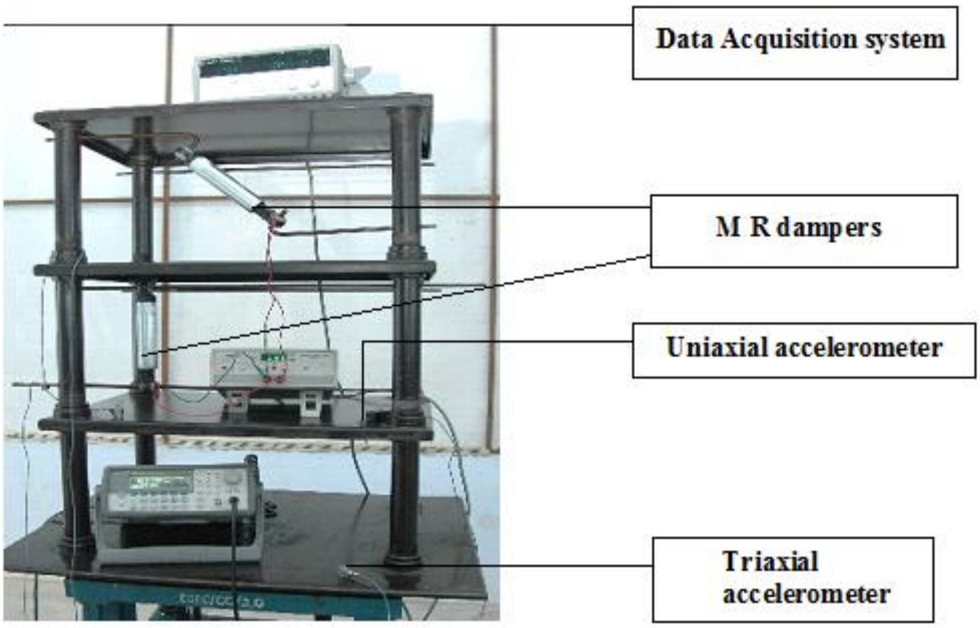

Figure 4: Photo Showing the Accelerometer and Transducer Placement